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13. ABSTRACT *(Maximum 200 words)*

Results of our research into the development and application of the positive (Cohen-Posch) time-frequency distributions (TFDs) are presented. These include (1) the development of a new computationally efficient weighted least squares method of implementation; (2) the development of a method to design informative priors for constructing Cohen-Posch TFDs; (3) studies of the relationship between instantaneous frequency and the conditional mean frequency of the positive TFDs, and the definition of the average frequency at each time; (4) a TFD based method of classification for nonstationary processes; (5) a new multi-window time-varying spectral analysis method; and (6) applications of the Cohen-Posch TFDs and conditional moments to machine vibration analysis and transient characterization. Copies of relevant publications are attached to the report.

14. SUBJECT TERMS Cohen-Posch time-frequency distributions, conditional mean frequency, moments, classification, multi-window time-varying spectral analysis, machine vibrations, transients.

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1. OBJECTIVES AND SPECIFIC AIMS

While great advances have been made in time-frequency analysis over the past several years, most current methods are limited in applicability to a small class of signals, and nearly all of these methods fail to provide theoretically sound joint energy density functions analogous to the spectral density of LTI processes (i.e., they fail to ensure nonnegativity and/or other properties required of a sound theory). This research addresses this limitation of current methods by developing and applying the positive time-frequency distributions (TFDs), which are a signal-dependent method of analysis applicable to a broad range of signals, founded in a sound theory.

The specific aims of this research are: (1) to develop new methods of implementation of the positive time-frequency distributions; (2) to further develop the theory of positive time-frequency distributions and explore its implications for new nonstationary signal processing tools, with extensions to physical quantities other than frequency; (3) to develop new methods for estimating positive time-frequency distributions of noisy signals; and (4) to apply these new methods to challenging, practical problems, including machine fault analysis and the study of elastic acoustic scattering.

2. ACCOMPLISHMENTS

We have made progress in each of the specific aims of this research, as follows.

2.1 New methods of implementation

Weighted Least Squares TFDs

We have developed a new WLS algorithm for implementing the positive (Cohen-Posch) TFDs. This new algorithm has advantages over a previously proposed least squares (LS) technique [Sang et al., ICASSP'96], and over the minimum cross-entropy (MCE) method previously developed by the PI [Loughlin et al., IEEE Trans. Sig. Proc., Oct. 1994]. The advantages of this new method are:

1. It is more computationally efficient for implementing conditional moment constraints (e.g., instantaneous frequency, group delay) than is the MCE technique.
2. It is far more computationally efficient than the LS algorithm given in [Sang et al., ICASSP'96].
3. It does not suffer from the "leakage" in the time-frequency plane that plagues the LS technique.

This new technique yields Cohen-Posch TFDs similar to those obtained using the MCE technique, and superior to those obtained using the LS algorithm. Details of this method, and examples, can be found in the attached manuscript, "Weighted Least Squares Implementation of Cohen-Posch Time-Frequency Distributions," by Emresoy and Loughlin, which has been accepted for publication in the *IEEE Transactions on Signal Processing*.

Informative Priors

We have developed a technique to enhance the information content of the Cohen-Posch TFDs, as quantified by their entropy and mutual information. To date, all of the optimization methods that have been developed for generating Cohen-Posch TFDs have as the first step the selection of an initial starting point, namely the "prior" estimate of the Cohen-Posch TFD. A constrained optimization is then performed to generate a Cohen-Posch TFD satisfying certain conditions (e.g., marginals, instantaneous frequency) that is closest to the prior in a minimum distance sense with respect to the optimization criterion (e.g., minimum cross-entropy,

least squares, etc.). Accordingly, selection of the prior is an important step that can have a significant affect on the outcome. Up until now, little effort had been directed at developing guidelines or methods for selecting the prior.

In our new approach, a prior is selected utilizing a minimum entropy / maximum average mutual information criterion, such that the final Cohen-Posch TFD has high resolution and high average mutual information. The average mutual information is a measure of how much more information is contained in the joint Cohen-Posch TFD than in its marginals.

Details of this method, and demonstration of its effectiveness, can be found in the attached reprint, "Informative priors for minimum cross-entropy positive time-frequency distributions," by Shah, Loughlin, Chaparro and El-Jaroudi, published in *IEEE Signal Processing Letters*.

2.2 Theory and new nonstationary signal processing methods

<u>The Time-Dependent (or Conditional) Mean Frequency of a Signal</u>

One of the contributions of our work on the development of the Cohen-Posch TFDs has been a reassessment of the interpretation of instantaneous frequency common in the time-frequency literature, namely that it is the average frequency at each time. This interpretation arises because many TFDs yield the instantaneous frequency for the first conditional moment,

$$\langle \omega \rangle_t = \varphi'(t) . \tag{1}$$

However, TFDs that yield this result take on negative values, and thus they are not legitimate density functions in the usual sense. Accordingly, conditional moments obtained from them may not be interpretable as true averages, and indeed they can often give absurd results (for example, the average value of squared frequency at a given time, $\langle \omega^2 \rangle_t$, which should clearly be positive, is very often negative for these TFDs, resulting in conditional standard deviations that are imaginary!).

The Cohen-Posch TFDs, which are legitimate densities, do not always yield eq. (1), and hence cast doubt on the common interpretation of instantaneous frequency as the average frequency at each time. Sometimes, however, the Cohen-Posch TFDs do yield eq. (1), and we have derived the cases when that occurs; they are limited in number. More significantly, we have found that for many multicomponent signals

$$x(t) = \sum_i a_i(t) e^{j\varphi_i(t)} \tag{2}$$

the Cohen-Posch TFDs yield a weighted-average of the individual instantaneous frequencies for the first conditional moment in frequency,

$$\langle \omega \rangle_t = \left(\sum_i a_i^2(t) \varphi_i'(t) \right) \Big/ \left(\sum_i a_i^2(t) \right) \tag{3}$$

which is generally not the instantaneous frequency of the signal. This quantity is bounded by the minimum and maximum value of the individual instantaneous frequencies of the signal components, and is interpretable as the average frequency at each time (unlike, in general, the instantaneous frequency). We are currently investigating situations under which other TFDs yield this result, (e.g., spectrograms), and also the question of how the conditional variance of a positive TFD relates to the instantaneous bandwidth as defined by Cohen.

Our results are reported in the attached papers, "Comments on the interpretation of instantaneous frequency," by Loughlin and Tacer, published in *IEEE Signal Processing Letters*; "Instantaneous frequency and the conditional mean frequency of a signal," by Loughlin and Tacer, published in the journal *Signal Processing*; "Time-varying frequencies of a signal," by Loughlin, published in the proceedings of the recent SPIE conference in San Diego; and "Spectrographic measurement of instantaneous frequency and the time-dependent weighted average instantaneous frequency," by Loughlin, which is in review for publication in the *Journal of the Acoustical Society of America*.

2

Classification

Building on our experience with positive TFDs and the conditional and joint moments of TFDs, we have developed a TFD moment-based method for nonstationary signal classification. Specifically, we extract joint moments from the TFD of the signals,

$$\langle t^n \omega^m \rangle = \int\int t^n \omega^m P(t, \omega)\, dt d\omega \tag{4}$$

and use these, after log- and variance-normalization, as input features to a classifier. For nonstationary processes, the method is effective and computationally inexpensive, once the classifier has been trained. In addition, by using a conventional classification algorithm such as Fisher's discriminant technique or a quadratic classifier, far fewer samples are needed to train the classifier than would be needed using a neural-net classifier.

The method has been tested on vibration transients in machining data, biomedical data, and synthetic cases, with encouraging results. For example, the method correctly distinguished between two different classes of chirp (differing in chirp rate, example TFDs shown below) buried in nonstationary colored noise and a tonal interference signal, whereas classification utilizing only temporal or spectral moments failed (Table 1). These very recent results are in preparation for submission to the journal *Pattern Recognition*. Some earlier results are reported in the attached paper, "Time-frequency based classification," *Proc. SPIE*, 1996.

Table 1: Classification Performance, Joint vs. Univariate Moments

Features Used	% correct (n=200)
Joint Moments	98
Spectral Moments	55
Temporal Moments	45
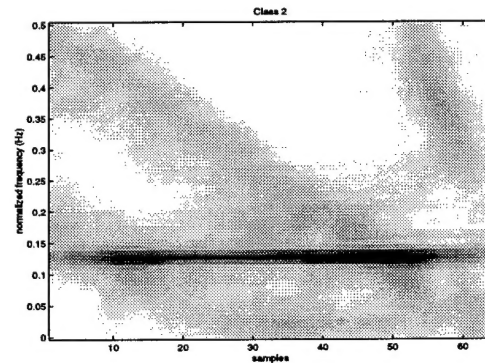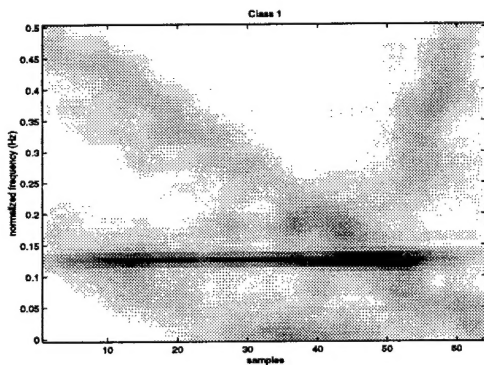
2.3 TFDs of noisy signals

For noise-free deterministic signal $x(t)$ with Fourier transform $X(\omega)$, the correct marginal densities of a TFD of the signal are $|x(t)|^2$ and $|X(\omega)|^2$. However, in many real-world signals, noise is present, e.g., $x(t) = s(t) + n(t)$, and the marginals of interest are those of the underlying noise-free signal, $E|s(t)|^2$ and $E|S(\omega)|^2$, where E denotes expected value (allowing for the possibility that the underlying signal is stochastic). Estimating these densities is not trivial, but it is clear that $|x(t)|^2$ and $|X(\omega)|^2$ are not likely to be good estimates to impose as marginal constraints. Rather, some smoothed version of these quantities is appropriate, which suggests smoothing or averaging the TFD of $x(t)$ to obtain an estimate of the TFD of $s(t)$.

To this end, we have developed an extension of Thomson's multi-window spectral estimation procedure to the time-frequency case. Our method is computationally simpler than other recent extensions of Thomson's

method, and further does not require a priori knowledge of the signal, unlike other methods. We compute N (typically 3-6) Hermite-windowed spectrograms of the signal $x(t)$, and optimally combine these to obtain a weighted average, where the weights are obtained by solving a least-squares problem. A nonlinear masking operation is also employed to eliminate extraneous sidelobes and interference, and the resulting TFD is far superior to a spectrogram or Wigner distribution of the noisy signal, as quantified by an SNR-like measure (for signals at SNR levels around 0 dB, the performance of our multi-window time-varying spectrum is 2-3 dB higher than that of a spectrogram, and several dB higher than that of a Wigner distribution; at higher input signal SNR levels, the improvement is even greater). Several examples and details of this method can be found in the attached manuscript, "Multi-window nonlinear time-varying spectral analysis," which has been submitted to the *IEEE Transactions on Signal Processing* for publication.

2.4 Applications

Machine Vibrations

We have applied Cohen-Posch TFDs to acoustic and accelerometer recordings of several vibration signals from various machining processes (e.g., drilling, milling, grinding), with the aim of identifying cues indicative of degradation, and to better understand the generation of machine faults. These TFDs clearly reveal time-frequency structure in machine vibrations that is related to the health of the machine and which is difficult or impossible to discern with conventional methods.

For example, in the analysis of a drilling operation, we have shown that Cohen-Posch TFDs reveal distinct changes in the spectral character of a drill bit with one chipped flute *per revolution*, and further that these features appeared in the TFD at least two holes prior to the detection of the problem using a conventional tool monitoring system. These results are reported in the paper "Cohen-Posch (positive) time-frequency distributions and their application to machine vibration analysis," published in *Mechanical Systems and Signal Processing*. (Figure 5 in the paper shows the drilling results.)

We have also utilized conditional and joint moments extracted from Cohen-Posch TFDs to monitor and classify machine degradation. In a milling operation, there were systematic changes in the conditional mean and median frequencies, as well as in the conditional bandwidths associated with these time-varying frequencies. These results are also reported in the paper cited above.

Characterizing Transients

We have applied time-frequency analysis to various acoustic transients, recorded by the PI while a US Navy-ASEE Faculty Research Fellow the previous summer at the Naval Surface Warfare Center, Bremerton, WA. Utilizing the theoretical developments in the definition and measurement of the time-varying average frequency (or conditional mean frequency), reported above in sctn. 2.2, we computed estimates of the conditional mean frequency and the conditional bandwidth for several transients. These conditional moments exhibit characteristic trends for different transients, which may be helpful in distinguishing between different classes of transients, and in understanding the underlying mechanisms generating the transient.

In the attached paper "Time-frequency analysis of acoustic transients," by Loughlin, Groutage and Rohrbaugh (ICASSP'97), we report dramatic differences in the conditional moments between two classes of transients, generated from different impact forces impinging on the same object, even though their spectral densities have many similarities (e.g., coincident peaks). Specifically, the time-varying trend of the conditional mean frequency is very different between the two classes. In the first class, conditional mean frequency decays rapidly from approximately 400 Hz to 100 Hz in the first 60 msec. The second class, however, exhibits an initial *rise* in conditional mean frequency from approximately 3 kHz to 6 kHz in about 20 msec, followed by a rapid decay from 6 kHz to 2 kHz in about 60 msec. The differences in conditional bandwidth are equally striking. Discussions of possible causes of the observed differences are made in the paper. The results clearly demonstrate that conditional moments offer a wealth of information beyond the spectral density, which can be useful in distinguishing between transients and understanding the mechanisms of transient generation and propagation.

3. PUBLICATIONS (COPIES ATTACHED)

1. M. Emresoy and P. Loughlin, "Weighted least-squares implementation of Cohen-Posch time-frequency distributions," accepted for publication in *IEEE Trans. Sig. Proc.*

2. S. Shah, P. Loughlin, L. Chaparro and A. El-Jaroudi, "Informative priors for minimum cross-entropy positive time-frequency distributions," *IEEE Sig. Proc. Lttrs.*, June 1997.

3. P. Loughlin and B. Tacer, "Comments on the interpretation of instantaneous frequency," *IEEE Sig. Proc. Lttrs.*, May 1997.

4. P. Loughlin and B. Tacer, "Instantaneous frequency and the conditional mean frequency of a signal," *Signal Processing*, July 1997.

5. P. Loughlin, "Time-varying frequencies of a signal," *Proc. SPIE Adv. Sig. Proc. Algs. VII*, vol 3162, July 1997.

6. P. Loughlin, "Spectrographic measurement of instantaneous frequency and the time-dependent weighted average instantaneous frequency," submitted to *J. Acoust. Soc. Am.* (in review).

7. B. Tacer and P. Loughlin, "Time-frequency based classification," *Proc. SPIE*, vol. 2846, 1996.

8. F. Cakrak and P. Loughlin, "Multi-window nonlinear time-varying spectral analysis," submitted to *IEEE Trans. Sig. Proc.* (in review).

9. P. Loughlin and G. Bernard, "Cohen-Posch (positive) time-frequency distributions and their applications to machine vibration analysis," *Mech. Syst. Sig. Proc.*, July 1997.

10. P. Loughlin, D. Groutage and R. Rohrbaugh, "Time-frequency analysis of acoustic transients," *Proc. IEEE ICASSP'97*, April 1997.

4. PLANS FOR UPCOMING YEAR

We are continuing research efforts in all four of the proposed specific aims. Efforts are underway to develop efficient methods for implementing moment constraints in the construction of Cohen-Posch TFDs. A new method is currently being implemented and tested. In preliminary experiments, we have been able to generate an accurate Cohen-Posch TFD of a chirp from only 25 joint moments. The more moments that can be implemented, the less dependent upon the prior estimate is the final Cohen-Posch TFD. Further, these moments could then also be utilized in our classification procedure, which we will also continue to develop. Some of the issues we will address here include the normalization of the moments, and the use of central moments.

Questions regarding instantaneous frequency and instantaneous bandwidth and their relation to conditional moments of a TFD will also be investigated. Specifically, is the conditional variance in frequency equal to Cohen's definition of instantaneous frequency, and if not, what does it equal in terms of signal parameters? As we have shown, the conditional mean frequency does not usually equal the instantaneous frequency, and we have given a new definition for the conditional mean frequency. We expect similar results to hold for the instantaneous bandwidth and conditional variance, and our investigations may then lead to a new definition for time-varying bandwidth. We will also investigate generalizations of these ideas to other variables, such as the conditional mean scale and the conditional scale bandwidth of a signal.

We will continue to develop the application of conditional moments to characterize acoustic transients, in collaboration with Mr. Bob Rohrbaugh and Dr. Dale Groutage at the Naval Surface Warfare Center. In particular, we believe that the time-varying mean frequency and the time-varying bandwidth are important in characterizing and understanding the propagation of transients. We will study these issues by generating and recording transient waves from well-defined structures to learn how these conditional moments change.

The estimation of the time-varying spectrum of noisy, nonstationary stochastic signals will also continue as a focus of our research efforts. We will develop methods for including inequality constraints in our multi-window approach (e.g., for imposing desired conditional and/or joint moments). Also to be investigated are questions of bias and variance for this method, as well as the use of other time-frequency based de-noising schemes for enhancing the TFD of noisy processes.